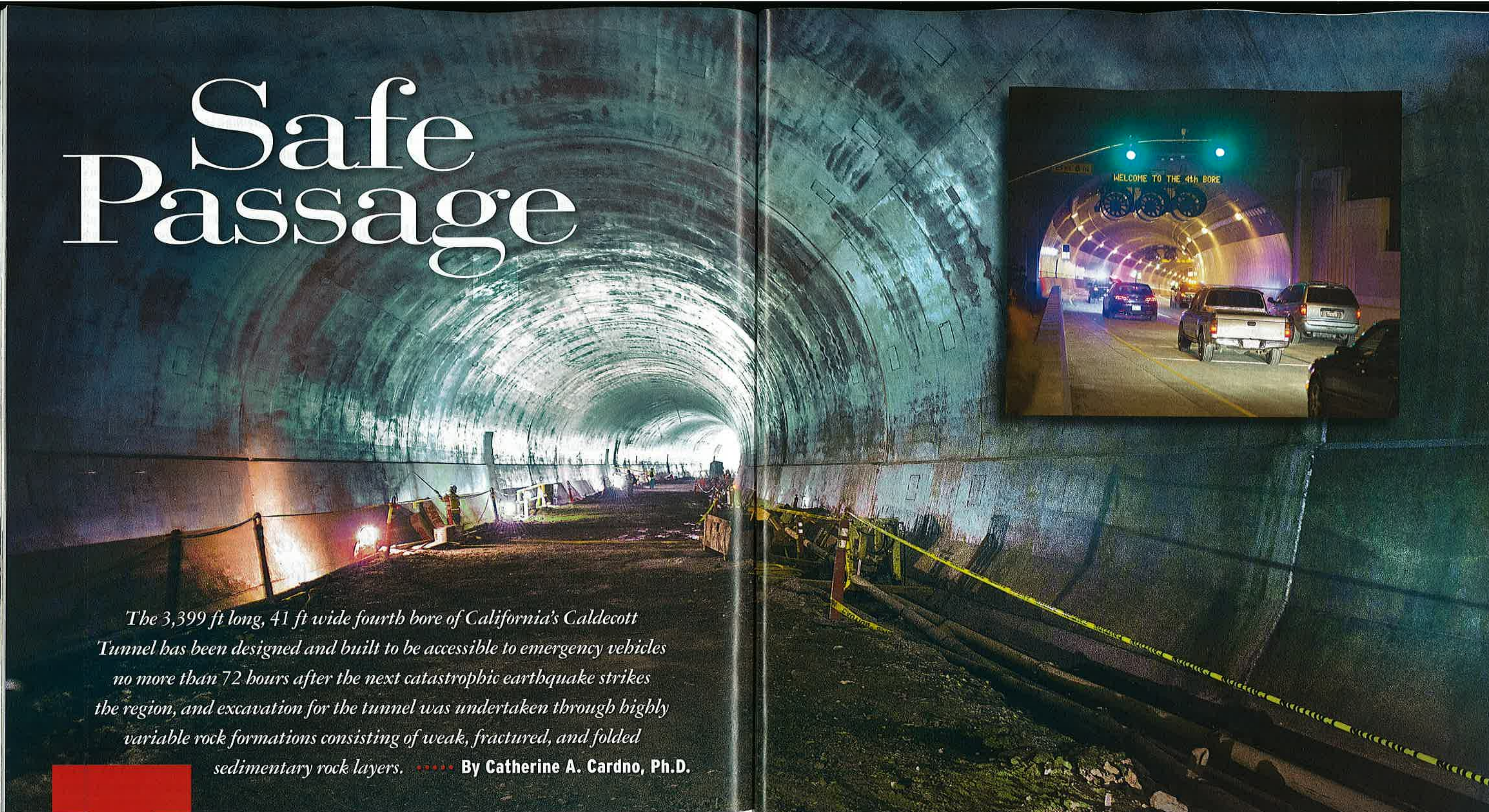

Safe Passage

The 3,399 ft long, 41 ft wide fourth bore of California's Caldecott Tunnel has been designed and built to be accessible to emergency vehicles no more than 72 hours after the next catastrophic earthquake strikes the region, and excavation for the tunnel was undertaken through highly variable rock formations consisting of weak, fractured, and folded sedimentary rock layers. **By Catherine A. Cardno, Ph.D.**

KARL NIELSEN, METROPOLITAN TRANSPORTATION COMMISSION, BOTH

The fourth bore of the Caldecott Tunnel opened to westbound traffic on Route 24 at 4:10 AM, *inset,* on November 16, 2013. The doubly reinforced concrete constituting the final lining of the tunnel is 1 ft 3 in. thick.

THE CITY OF SAN FRANCISCO IS well known for many things and among the most memorable are its steep hills and propensity for earthquakes. These characteristics, however, are by no means limited to the peninsula. The Caldecott Tunnel, which connects a network of freeways in California's Contra Costa County with the Bay Area's Alameda County and Oakland, opened its fourth bore on November 16, 2013, and had to address challenges arising from both characteristics.

"It is safe to say that in the event of a catastrophic earthquake in the Bay Area, this would be a significant lifeline route to support logistics operations for the event," said Lori Newquist, a spokesperson for the Governor's Office of Emergency Services, who wrote in response to questions posed by *Civil Engineering.* "That would include support from the state or federal government," Newquist said. Route 24, which extends through the Caldecott Tunnel, offers a connection between the Bay Area and the Central Valley, as well as areas that would be undamaged by a catastrophic earthquake.

The Caldecott Fourth Bore Project was a joint effort by the Federal Highway Administration, the California Department of Transportation (Caltrans), the Metropolitan Transportation Commission, the Contra Costa Transportation Authority, and the Alameda County Transportation Commission. The San Francisco office of the engineering firm Jacobs Associates led the design work for the new bore, and Parsons Transportation Group, which is based in Pasadena, California, was the prime design consultant and handled the preliminary engineering and final design of the cut-and-cover tunnel sections at each end of the bore and of the

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operations and substation buildings. Caltrans was in charge of construction management and handled the roadway design portion and some of the retaining walls.

"We decided at the [beginning] to really follow a different way of delivering projects in the state of California," says Cristina Ferraz, P.E., the Caltrans project manager for the new bore. "We decided to create a one-team approach... and this approach worked extremely well." Rather than Caltrans reviewing and rejecting drawings after the consultants had completed them, she explains, Caltrans and the consultants worked collaboratively to develop the tunnel and roadway plans.

"We're very proud to state that this project has been completed on time. Actually, it was a little bit ahead of time... and below budget," Ferraz says. "So it has been a tremendously successful project here in the state of California—a major infrastructure, $417-million project that was completed on time and below budget."

The first two bores of the Caldecott Tunnel, each 3,610 ft long and nearly 27 ft wide, were opened in 1937, according to material provided by Caltrans. A third bore, this one 3,771 ft long and 28 ft wide, opened in 1964, making it possible to offer a reversible route depending on traffic demands. With an average daily traffic count of almost 160,000 vehicles moving between Contra Costa County and the Bay Area before construction work on the fourth bore was completed, tunnel operators would reverse traffic in the middle bore twice a day on weekdays and as much as half a dozen times a day during weekends, particularly if special events, concerts, or sporting events were taking place in the Bay Area, according to Caltrans.

The fourth bore provides two dedicated lanes for westbound traffic, so four lanes of traffic can remain open at all times in both directions. "With the opening... of the Caldecott fourth bore and the recent opening of the Tom Lantos Tunnels—the Devil's Slide tunnels in Pacifica—the California Department of Transportation has delivered two state-of-the-art tunnels within the year," says Randy R. Anderson, P.E., the structural design manager and consultant design oversight manager for Caltrans. "The last significant roadway tunnel to be built in California was the third bore of the Caldecott, completed in 1964," he notes.

The size of the fourth bore, at 3,399 ft long, 26 ft high, and 41 ft wide, "makes it California's largest roadway tunnel when considering the ratio of the length to width," Anderson says. The tunnel contains two 12 ft wide lanes, two shoulders—one 10 ft wide and the other 2 ft wide—a 3 ft emergency walkway, and a 2 ft wide curb.

The bores cut through the Berkeley Hills, which encompass three primary rock formations that date to the Miocene (23 million to 5.3 million years ago). "The maximum cover over the tunnel is approximately 525 feet below the local high point of the Berkeley Hills, at an elevation of 1,400 feet," said Michael McRae, D.Eng., P.E., G.E., M.ASCE, a principal in the San Francisco office of Jacobs Associates, who wrote in response to questions posed by *Civil Engineering*. Looking back on the project, McRae, who led the tunnel design for the fourth bore, said, "The major technical design challenge for the project involved developing excavation sequences and support systems that allowed safe and efficient mining and support operations in the highly variable, fractured, and weak rock formations."

The western end of the tunnel, on the Oakland side, in Alameda County, extends through the Sobrante Formation, a marine shale and sandstone layer, while the

A gantry system with a frame that slid along a track facilitated the installation of the tunnel waterproofing and final lining.

KARL NIELSEN, METROPOLITAN TRANSPORTATION COMMISSION

A 130-ton roadheader began the excavation of the bore in August 2010 and moved on tracks from east to west to excavate the tunnel's top portion.

JOHN HUSEBY, CALTRANS

middle of the tunnel passes through the Claremont Formation, which features chert, shale, and sandstone. The eastern end of the tunnel, inland in Contra Costa County, passes through the Orinda Formation, a nonmarine clay stone, siltstone, sandstone, and conglomerate layer. Four major faults and three minor faults are located in the area near the fourth bore, although the bore does not pass directly through any active fault.

Because of the variability of the rock formations, the sequential excavation method, also referred to as the new Austrian tunneling method, was used to construct the fourth bore, according to Anderson. Excavation proceeded from both ends of the tunnel simultaneously, each end featuring a 75 ft long cut-and-cover section, according to Anderson. "The portion of the tunnel constructed with [the sequential excavation method] consists of an initial lining and support, which was used to support the tunnel during excavation, and a 1-foot, 3-inch doubly reinforced concrete final lining supported on large footings," Anderson says.

Good engineering also conferred economic benefits. "Our design also allowed for load sharing between the initial ground support and the final lining, which resulted in considerable cost savings for the project," McRae noted.

"We were fortunate we had Jacobs Associates, and they had one engineer, the late Bhaskar Thapa, Ph.D., P.E., M.ASCE, who was an expert in this area and who developed the excavation sequence with seven support categories," Anderson says. "We also had him in the field... evaluating construction, evaluating the condition of the rock and soil after the contractor was doing his excavation,... making daily determinations, [and asking,] 'Are we in the correct ground that we have on the drawings? Do we need to modify?'" Anderson recalls. "Because of all that, that was a huge success having Bhaskar doing the design [and] having him in the field."

Careful attention was given to deformation. "The team performed state-of-the-practice analyses to evaluate the deformation of the tunnel when subject to ground shaking... and developed the design for the tunnel lining system to accommodate the predicted seismic deformations and loads," McRae explained.

Because of the variability of the rock layers, a variety of support systems were used. "An initial excavation category might include installing lattice girders, spiles, rock bolts, or pipe canopies and then, once they got that in place,... concurrently they would apply a thin layer of [fiber-reinforced] shotcrete to get their initial support," Anderson says. The most extensive initial ground support, which included large pipe canopies, lattice girders, and an invert arch, was at the western end of the tunnel, where the geological formation was weakest, he notes.

A waterproof membrane was placed atop the final shotcrete layer to direct water to an underground drainage system at the bottom of the tunnel. The double-layer rebar cage was topped with a concrete layer that integrated a mix of polypropylene fibers to improve the resistance to explosive concrete spalling in the event of a severe fire, according to Anderson. Steel panels coated with porcelain enamel were attached to the lower portion of the final lining.

"Due to the regional importance of the tunnel area on... Route 24, it was determined that the tunnel and its supporting structures would be designed as important structures," Anderson says. "In the past we called those lifeline routes, but we're changing the designation... more to a recovery route," he says. "We're steering away from the use of [the term] 'lifeline' [because] all the routes are important to a region."

"Important" structures are evaluated and designed to meet two different design earthquakes, Anderson says, "one being the safety evaluation earthquake, which we call the SEE, and the other being the functional evaluation earthquake. The design team adopted a 1,500-year return period for the SEE event and a 300-year return period for the [functional evaluation earthquake] event based on the probabilistic seismic hazard evaluation," Anderson says. Because of the time frame of construction, he notes, the design also encompassed a construction evaluation earthquake with a 100-year return period to protect the workers at the site.

"Tunnels are rarely significantly damaged except where fault offsets or ground failure occurs," Anderson explains. "The Hayward Fault is about a mile west of the tunnels, and the new tunnel is not crossing a significant active or potentially active fault and no evidence existed that ground failure could occur." To enhance performance and ductility, the lining of the fourth bore and the connection points of the passageways linking the third and fourth bores were tied together structurally with the double layer of reinforcement and ties, according to Anderson.

"The arch itself is a very efficient structural member," Anderson says. "When you look at the moment interaction diagram, even with the seismic loads on there, we don't exceed the capacity of the arch system. So that's why in our analysis we showed that this tunnel is not vulnerable even at the SEE event." As he explains, "You've got to consider your buildings, and you've got to consider your walls also and anchoring down your equipment to handle these earthquake loads."

More than 15 major retaining walls, the longest extending almost 1,000 ft, along with a number of minor retaining walls, were constructed to stabilize the slopes around the tunnel. Six of the large walls were for the cut-and-cover portions at the tunnel ends. Use was made of "all different types of retaining walls: soil nail walls, tieback walls, secant walls, and soldier pile walls," Anderson says. "For the cut-and-cover portal head, we had to break through the lower portion of the retaining wall to start the mining operation."

Slope movement was another important consideration. "One of the criteria for the SEE is [that] we wanted to limit slope movement [because] we didn't want the slope behind the walls being able to move that far out," Anderson explains. "We increased the capacity of the retaining walls to limit how much those slopes could move into the wall."

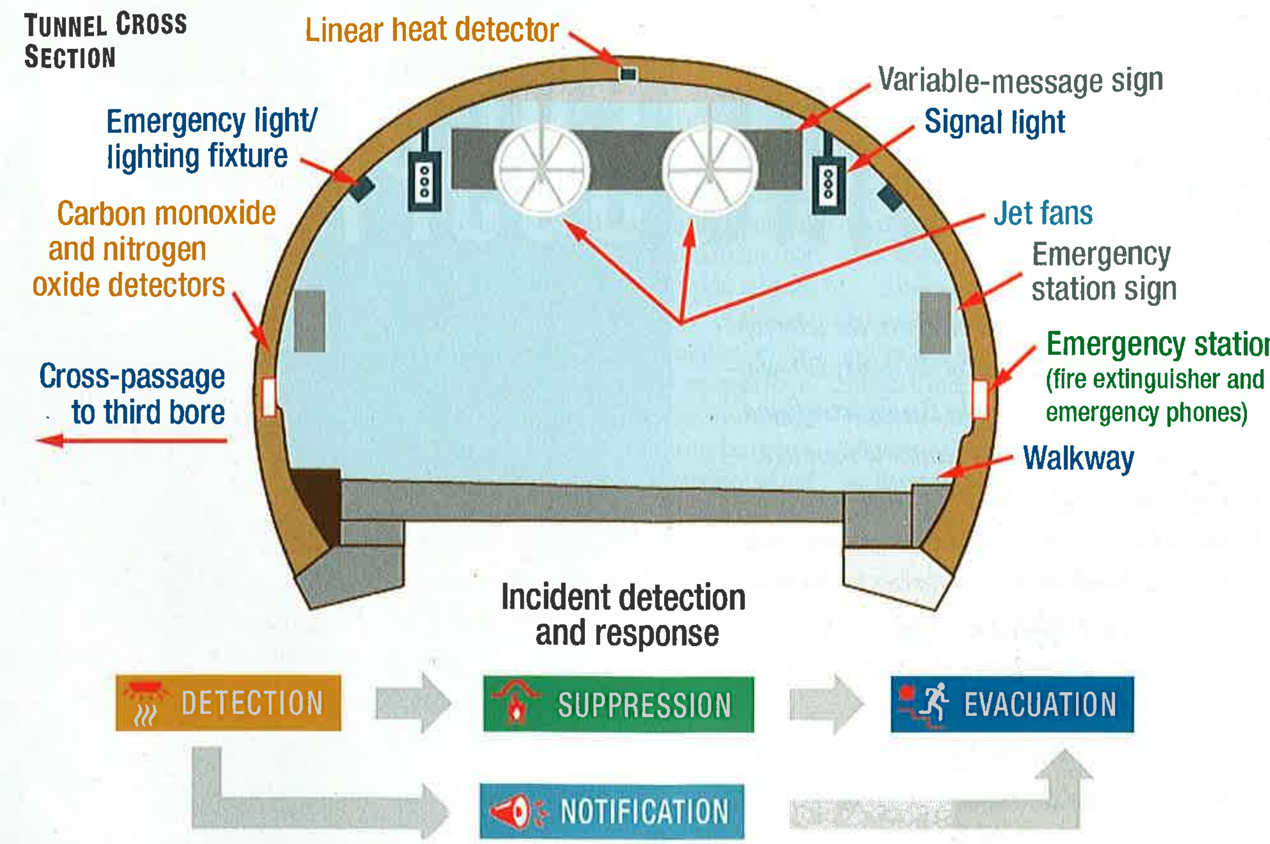
A severe fire in the third bore in 1982 led to revisions of the *California Vehicle Code* that confined the transport of hazardous materials through the tunnel to the hours of 3 AM to 5 AM, according to Anderson. That fire and subsequent tunnel fires in the United States have resulted in updated National Fire Protection Association codes and standards, and the fourth bore has been designed to meet current nationwide codes, he says.

"Although tunnel fires may never be able to be completely avoided inside tunnels—or anywhere, for that matter—the tunnels that are being designed and constructed today have some of the most advanced features to minimize the damage of fires and to safely evacuate the users of the tunnel," Anderson says.

The entire roadway slopes 2 to 5 degrees in one direction, directing any spills to a precast slotted drain system that is designed with a baffling basin to handle spills of hazardous liquids, according to Anderson. "If you get a hazardous spill, you want to get that liquid off the roadway as quick as possible. You don't want that pooling and to become more of a source for the fire," he says. The liquid passes through a narrow neck to the drainage system, which widens into a large oval. The baffling system encloses liquid to trap and extinguish any flames that might be present. "That's really state of the art for roadway drainage inside tunnels," Anderson says.

Workers celebrated when the top portions of the east and west sides of the tunnel met.

KARL NIELSEN, METROPOLITAN TRANSPORTATION COMMISSION



METROPOLITAN TRANSPORTATION COMMISSION

Seven passageways linking the third and fourth bores provide ventilated, safe egress routes, and communications systems will enable operations personnel to provide information to those within the passageways.

The ventilation system for the fourth bore includes 19 jet fans that can clear smoke and provide visibility for firefighters entering and motorists exiting. "The shape of the tunnel was selected in large part because of its efficiency in providing the required horizontal roadway clearance and vertical clearance requirements with a longitudinal jet fan ventilation system," Anderson says.

Other safety elements include dedicated emergency water lines that run through the tunnel, emergency stations with fire extinguishers and emergency phones, variable-message signs that tell drivers to slow down or stop because of accidents, barriers that can be activated remotely to close the tunnel at the entrance portals, and signs on the walls giving the distance to the next passageway or to the portal. To address problems of limited visibility, the side of the tunnel with the passageways to the third bore has a green stripe on the porcelain enamel coating so that motorists can quickly determine the direction in which they should move.

A newly constructed two-story operations and maintenance building monitors all four bores, as well as the passageways linking them, via a closed-circuit television supervisory control and data acquisition system 24 hours a day seven days a week. Substations located atop the portals at both ends of the fourth bore can provide backup power for the tunnel, so the systems will remain in operation even in the event of a widespread power outage on either side of the tunnel. In the event of an accident or incident at the operations and maintenance building, a backup room located outside provides full access to the monitoring and control systems for all four bores, according to Ferraz.

The Caldecott Fourth Bore Project involved four construction contracts and was partially funded by bonds issued by the State of California, Ferraz notes. The undertaking also received $120.6 million in local tax monies from Contra Costa County's Measure J, as well as $194.3 million in federal funds from the American Recovery and Reinvestment Act of 2009, according to Caltrans.

Parsons Brinckerhoff, a global consulting firm headquartered in New York City, and Gall Zeidler Consultants, a global geotechnical engineering, tunnel engineering, and construction firm headquartered in Ashburn, Virginia, provided construction support to Caltrans for the project.

Tutor-Saliba Corporation, an international contracting firm headquartered in Sylmar, California, was the prime construction contractor on the project. **CE**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